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TRAVEL TIME ESTIMATION ON URBAN STREET SEGMENT

ABSTRACT

Level of service (LOS) is used as the main indicator of transport quality on urban roads and it is estimated based on the travel speed. The main objective of this study is to determine which of the existing models for travel speed calculation is most suitable for local conditions. The study uses actual data gathered in travel time survey on urban streets, recorded by applying second by second GPS data. The survey is limited to traffic flow in saturated conditions. The RMSE method (Root Mean Square Error) is used for research results comparison with relevant models: Akcelik, HCM (Highway Capacity Manual), Singapore model and modified BPR (the Bureau of Public Roads) function (Dowling - Skabardonis). The lowest deviation in local conditions for urban streets with standardized intersection distance (400-500 m) is demonstrated by Akcelik model. However, for streets with lower signal density (<1 signal/km) the correlation between speed and degree of saturation is best presented by HCM and Singapore model. According to test results, Akcelik model was adopted for travel speed estimation which can be the basis for determining the level of service in urban streets with standardized intersection distance and coordinated signal timing under local conditions.

KEY WORDS

urban street; level of service; speed-flow curve; travel time survey;

1. INTRODUCTION

LOS is used as the main transport process quality indicator on urban streets. The input variable for LOS estimation on urban streets is travel speed which can be determined analytically or empirically. The speed is calculated using section's length and section travel time, depending on section and control delay. Intersection delays have the largest share in travel time and their assessment is the key step in determining LOS. In the process of speed estimation some analytical models directly take into account delays at intersections. Beside them, models describing travel speed and degree of saturation correlation, without taking into account signal timing parameters, are also present in literary sources.

Since signalized arterials are subject of this analysis, travel time, and therefore travel speed will depend on control delay. This study is examining four models illustrating correlation between average speed and degree of saturation (HCM, Akcelik and Singapore model and Dowling- Skabardonis) in comparison to actual data gathered through survey on urban streets.

In literary sources, the results obtained by model use are usually compared to actual data in an attempt to determine which better presents the particular conditions, or which better suits the particular type of urban street. That is the reason why Mtoi and Moses examined the use of different models for presenting the average travel speed and degree of saturation correlation for different street categories [1]. By comparing Akcelik model, modified BPR, modified Davidson and Conical function, it was concluded that Akcelik model provides the smallest RMSPE (Root Mean Square Percent Error) for signalized arterials in comparison to data gathered in the study. Ali, Venigalla and Flannery focused on travel time assessment, depending on street geometry and traffic parameters [2]. The authors developed a survey data based regression model and then compared the results from this model and HCM analytical procedure. They concluded that HCM underestimates the travel speed on smaller sections (<0.5 mile). The application of non-parametric Singapore model estimated the smallest RMSE in comparison to other models [3]. Results showed that this model can estimate the travel speed with deviation of 5 km/h in 95% of time. In their studies Dowling and Skabardonis compared BPR, exponential function and Akcelik model and concluded that all the applied functions and models provide good results for conditions below the saturation threshold [4]. However, the Akcelik model best illustrates the impact of degree of saturation on the speed, in comparison to presented functions in saturated conditions. Literature review recognizes models that can describe the current situation on a specific urban street type. This study further presents the selected models.

2. MODELS FOR TRAVEL SPEED ESTIMATION

HCM model

Practical procedure of determining LOS according to HCM is based on the values of average operational speed on the section of network. Average speed on previously defined section of certain network category is represented by the following expression:

$$V = \frac{3,600 \cdot L}{T_j \cdot L + d_s} \tag{1}$$

where:

V – average speed on section with length L [km/h];
L – section length [km];
T_j – unit travel time on section reduced to 1 kilometre length, in function of road category [s/km];
d_s – control delays on section resulting from certain mode of control [s];

Control delays value is determined by the following expression [5, 6]:

$$d = PF \cdot d_1 + d_2 + d_3 \tag{2}$$

$$d_1 = \frac{0.5 \cdot C \cdot [1 - \lambda]^2}{1 - [\min(1,x) \cdot \lambda]} \tag{3}$$

$$d_2 = 900 \cdot T \cdot \left[(x - 1) + \sqrt{(x - 1)^2 + \frac{8 \cdot k \cdot I \cdot x)}{c \cdot T}} \right] \tag{4}$$

where:

d – control delay at signalized intersection [s/veh];
d_1 – uniform delay [s/veh];
d_2 – incremental delay [s/veh];
d_3 – initial queue delay [s/veh], a value of zero is used for d_3;
PF – progression adjustment factor;
C – cycle length [s];
λ – effective green proportion [g/C];
x – volume to capacity ratio (v/c) for the lane group;
c – capacity [veh/h];
T – duration of analysis period [h];
k – incremental delay adjustment for the actuated control;
I – incremental delay adjustment for the filtering or metering by upstream signals;

HCM analytical procedure for LOS assessment is simplified by the use of speed-degree of saturation curves. The curves are created based on road category and number of signals per mile. HCM road categories have clearly defined geometry, method of flow servicing at intersections, presence of parking space, connections, etc., as well as free flow speed.

The HCM curves main deficiency is that they are created for arrival type 3 (random arrival of vehicles) which cannot be applied to urban streets with coordinated signal timing and standard intersection distance of approximately 500 m. In local conditions, the deficiency of applying these curves lies in the fact that the city streets, subject of the research, do not strictly belong to any category defined by HCM. More specifically, HCM recommends taking the category which corresponds to the estimated free flow speed. The streets, the subject of research, correspond to the free flow speed specified for category II, while the geometric characteristics better correspond to category III.

HCM analytical procedure for determining the travel time does not include any calibration parameter. Parameter values in the model depend on the signal timing parameters, and street category. Also, HCM model requires a large amount of data.

Akcelik model

Akcelik model represents the modified Davidson function to avoid the problem of parameter calibration in Davidson function [7].

$$t = t_0 + 3,600 \cdot \left\{ 0.25 \cdot T \left[(x - 1) + \sqrt{(x - 1)^2 + \frac{8 \cdot J_A \cdot x}{c \cdot T}} \right] \right\} \tag{5}$$

t – average link travel time [s];
t_0 – free flow link travel time [s];
J_A – calibration parameter;

J_A is a parameter of delay, depending on p, number of signals per length unit, and parameter k, defining the signal timing method. Parameter k has the value of 0.6 for isolated and 0.3 for coordinated sections. However, due to delays which may occur during data collection runs due to, for example, pedestrian crossings, bus stops, etc., it is necessary to modify this parameter further [7]. Akcelik presents parameter values to be expected based on actual data. The assumption is based on minimum speed, lane capacity and delays for defined road categories. Dowling and Skabardonis emphasize the benefits of this model as it provides extremely good results for saturated conditions [4].

Skabardonis – Dowling model

Skabardonis - Dowling model has improved the BPR function, which for signalized sections has the following form [8]:

$$V = \frac{V'_{FFS}}{1 + 0.05 \cdot x^{10}} \tag{6}$$

Free flow speed is reduced by factors such as number of signals on the link, link length and delays as a result of light signal presence. Delays calculation is taken from the HCM 1994. The reduced free flow speed is calculated according to formula [8]:

$$V'_{FFS} = \frac{L}{\frac{L}{V_{FFS}} + \frac{d \cdot N}{3,600}} \tag{7}$$

V'_{FFS} – adjusted free flow speed (considering the presence of signals) [km/h];

V_{FFS} –free flow speed [km/h];
N –number of signals;

This model type is proposed for sections where the signals are placed at the distance equal to or less than 3.2 km [8].

Singapore model

This model is a nonparametric model illustrating correlation between travel time and degree of saturation taking into account signal timing parameters. Travel time is defined as a sum of cruise time and control delay. To estimate the delay at intersections, the modified Webster formula is used in model [3]:

$$t=\frac{3,600\cdot L}{V_{FFS}}+\frac{9}{10}\left[\frac{C(1-\lambda)^2}{2(1-\lambda\cdot x)}+\frac{x^2}{2\cdot q(1-x)}\right] \tag{8}$$

q –arrival rate [veh/s].

The deficiency of this model is its limited application. This model, together with Webster model for estimation of delay, has limits when it comes to its application for the degree of saturation equal or higher than one [9].

3. METHOD AND TECHNIQUE OF DATA GATHERING

The recording of actual test car trajectories was conducted in the study. Floating vehicle method was applied, representing one of the standard methods of researching the indicators of the urban transport system state, based on a small sample research. Trajectory recording was executed by GPS technique based on continuous recording, with one second frequency. Simultaneously to travel time study, the traffic count was conducted at intersections along the defined sections, where surveyed travel time was studied.

Figure 1 presents the speed changes along the monitored artery, including more passes of test cars.

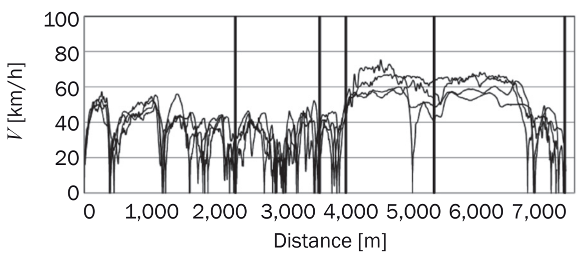

Figure 1 – Speed profile recorded using second by second GPS data on surveyed section

Travel time survey was carried out on two sections with multiple vehicle runs, during several periods during the day, in order to cover various conditions in the traffic flow. Surveyed sections met the following requirements:

- Presence of signalized intersections at an average distance of 400 m;
- Presence of raised median separating the directions;
- Separate lanes for left turns accommodated in protected phase;
- Bus stops in the right lane;
- No parking;
- Average λ of 0.45 for straight flow;
- Coordinated signal timing;
- Speed limit of 50 km/h;
- Straight flow capacity of approximately 1,800 veh/h.

4. SURVEY RESULTS

Data processing included:

- degree of saturation estimation on the section based on traffic count, straight flow volume was estimated at each signalized intersection on observed section. The degree of saturation was calculated according to the capacity of each intersection along the artery.
- travel speed estimation on the section resulting travel speed represents the average value of all recorded speeds in one test car run on the observed section. Sections are defined from the middle part of the previous intersection to the middle part of the following one, to include the speed change generated as a result of signal function referring to the process of deceleration, stopping and acceleration. This way, the section for each pass is defined by determined values of travel speed and degree of saturation. (*Figure 2*).
- creation of degree of saturation categories.

In further data processing, the categories of the degree of saturation were formed, in steps of 0.1. For each category, the average of related travel speeds was determined. Due to the lack of data on travel speed, especially for lower degree of saturation values, i.e. in free flow conditions, it was not possible to create categories in a smaller range.

The resulting average travel speed for each category was compared with the travel speed values obtained by the presented models (HCM, Akcelik time travel function, modified BPR function (Skabardonis - Dowling model) and nonparametric Singapore model) (*Figure 3*).

Based on the values obtained by the presented models, it can be concluded that the curve created by Akcelik model has a shape which suits the actual data most adequately. This shape is also produced by Singapore model, but it significantly underestimates the travel speed (≈18 km/h). Based on the speed values from the research, significant decline of speed value for the degree of saturation higher than 0.65 is obvious. Such a decline cannot be reached by HCM curve and modified BPR function curve (Skabardonis - Dowling model). The speed values obtained by HCM model are lower than the ones measured in the study,

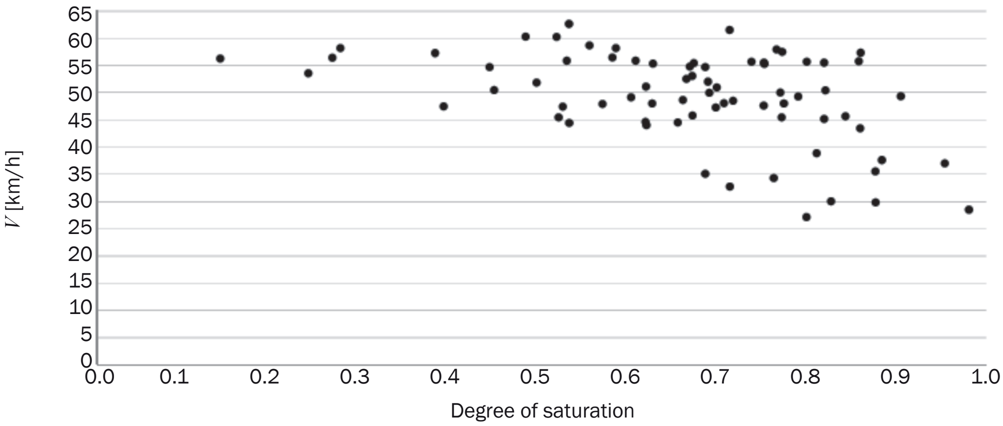

Figure 2 – Average travel speed for given degree of saturation determined by measuring

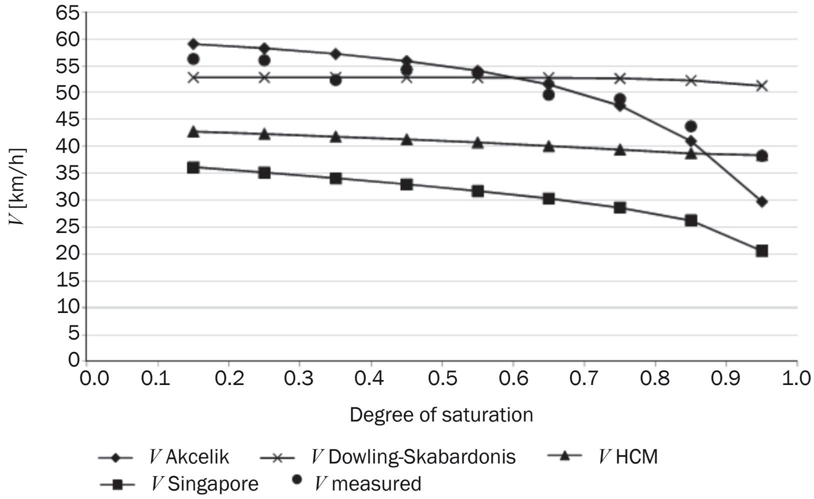

Figure 3 – Speed-degree of saturation relationship for fitted function and measuring data

approximately 11 km/h for speeds in the degree of saturation lower than 0.65, while for larger values the absolute error is reduced to approximately 5 km/h. The modified BPR function (Skabardonis - Dowling model) gives better results at a lower degree of saturation (<0.65), but beyond this rate it increases the value of absolute error.

In addition to graphical analysis of the results, statistical methods for model assessment are used in further processing. The most frequently applied statistical methods are root-mean-square error (RMSE), the root-mean-square-percent error (RMSPE), the mean error (ME) and the mean percent error (MPE). For each of the compared models, the study shows the difference between the speeds obtained by the research and by specific models by applying the indicators root-mean-square error (RMSE) and Theil's inequality coefficient (TIC).

RMSE - These statistics quantify the overall error of the model. The RMSE penalize large errors at a higher rate relative to small errors. The measure is given by:

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (V_{pred} - V_{obs})^2} \qquad (9)$$

N – number of observations;
V_{pred} – predicted speed [km/h];
V_{obs} – observed speed [km/h].

Another measure that provides information on the relative error is Theil's inequality coefficient, TIC:

$$TIC = \frac{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (V_{pred} - V_{obs})^2}}{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (V_{obs})^2} + \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (V_{pred})^2}} \qquad (10)$$

TIC – circumscribed as $0 \leq TIC \leq 1$;
N – number of observations;
V_{pred} – predicted speed [km/h];
V_{obs} – observed speed [km/h].

When TIC=0, it signifies perfect fit between the observed and predicted speeds from the model. When TIC=1 it implies the worst possible fit. *Table 1* shows the determined values of RMSE and TIC observed by the applied models.

Table 2 – Determined RMSE values by models applied for different distances between surveyed intersections

Model	RMSE 400m	RMSE 1,000m	RMSE 1,500m
Akcelik	3.54	5.09	6.41
Dowling – Skabardonis	5.90	5.73	5.32
HCM	8.93	4.38	4.58
Singapore	18.64	6.66	3.39

Table 1 – Determined values of RMSE and TIC observed by the applied models

Model	RMSE	TIC
Akcelik	3.54	0.03
Dowling – Skabardonis	5.90	0.06
HCM	8.93	0.10
Singapore	18.64	0.23

Based on the presented results it can be concluded that Akcelik model describes the obtained data with the lowest error. The worst match is achieved with the Singapore model. For the adopted Akcelik model, the calibration of parameter J_A was carried out to minimize the RMSE (root mean square error) between the travel speed gained through research and through the model, although its value deviates from the proposed value of parameter J_A for the specific street type [7].

Following the adoption of Akcelik model which represents the correlation between speed and degree of saturation for this type of city streets, the authors also tested this model on the same street type but with bigger intersection distances. By comparing the obtained and actual data, it was determined that the presented models are sensitive to intersection distances.

Table 2 shows the determined RMSE values by models applied for different distances between surveyed intersections.

HCM and Singapore model provide significantly better results or lower RMSE with the increase of intersection distance, while distance increase raises the RMSE between empirically determined values and Akcelik model. By applying Singapore model on city streets where the intersection distance is approximately 400 m and on sections where it is approximately 1,500 m, RMSE decreases from 18.64 km/h to 3.39 km/h, indicating that this model could be used on sections with a lower number of signals per kilometre (0.66 s/km). The use of modified BPR function (Dowling - Skabardonis model) on locations with varying signal frequency per kilometre produces approximately constant RMSE values. The error in travel speed assessment is in the range of 5.32-5.90 km/h. The conclusion is that the model mentioned above can be applied to both types of urban streets covered in the study.

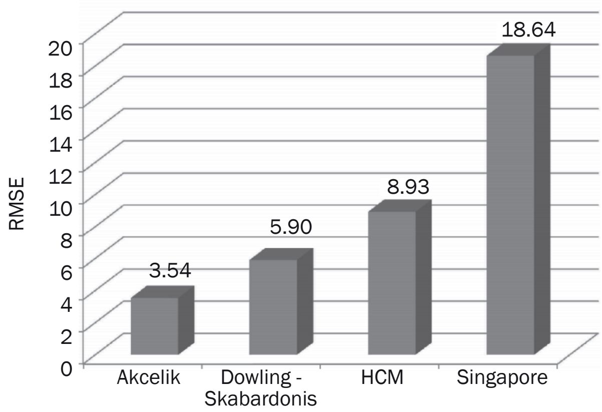

Figure 4 – RMSE for section length of L=400 m

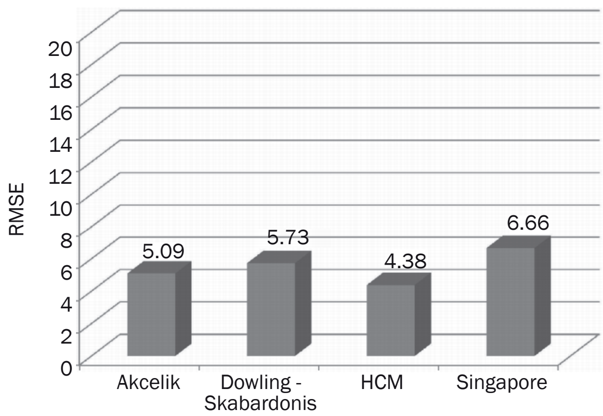

Figure 5 – RMSE for section length of L=1,000 m

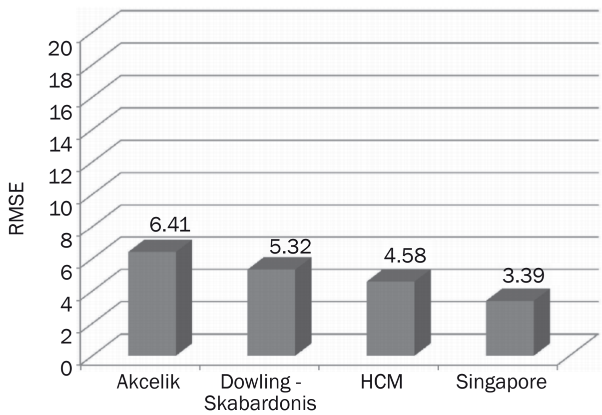

Figure 6 – RMSE for section length of L=1,500 m

5. CONCLUSION

Travel speed is directly dependent on the degree of saturation. The extent to which the saturation level will influence the increase of the delay also depends on the signal timing parameters. This paper tried to establish a relation between travel speed and degree of saturation through the models, directly containing signal timing parameters. Through research and results from the model it was concluded that the Akcelik model is the most suitable one for sections with higher number of signals per length unit. In Akcelik model, the calibration of parameter J_A was performed to minimize the RMSE, although there are recommended values of this parameter. City streets have standard intersection distance (≈400 m); however, longer distances are also present on the network and that is why it was necessary to test the possibility of applying Akcelik model on this type of sections as well. The proposed models showed sensitivity to signal frequency change. It was determined that at longer distances (>1,000 m) smaller mistakes are produced by the HCM and Singapore model. This leads to the conclusion that a unique model cannot be applied to all types of urban streets, except when the accuracy of travel speed estimation is not emphasized (application of Dowling - Skabardonis model). Depending on the management mode and geometric characteristics of the streets it should be examined which model, describing this correlation, best suits the local conditions. Future research will include formulation of models used to describe, with the lowest RMSE, the correlation of speed and degree of saturation on other types of urban streets, where additional research would be necessary.

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ESTIMACIJA VREMENA PUTOVANJA NA GRADSKIM SAOBRAĆAJNICAMA

SAŽETAK

Nivo usluge (NU) se koristi kao osnovni pokazatelj kvaliteta saobraćajnog procesa na gradskim saobraćajnicama. NU se procenjuje na osnovu eksploatacione brzine. Osnovni cilj rada je da se utvrdi koji od postojećih modela kojim se proračunava eksploataciona brzina najviše odgovara lokalnim uslovima. U radu su korišćeni realni podaci dobijeni iz istraživanja vremena putovanja na gradskim saobraćajnicama, snimljeni primenom second by second GPS data. Istraživanja su ograničena na uslove saobraćajnog toka do granice zasićenja. Metoda RMSE (root mean square error) je primenjena u poređenju rezultata dobijenih istraživanjem sa relevantnim modelima Akčelikov, HCM-ov, Singapur model i modifikovanu BPR funkciju (Dowling – Skabardonis). Utvrđeno je da se u lokalnim uslovima najmanja odstupanja dobijaju Akčelikovim modelom za gradske saobraćajnice sa standaradnim rastojanjem između raskrsnica (400-500m). Međutim, za arterije sa manjom gustinom signala (<1 sig/km) dobijeno je da se zavisnost brzina – stepen zasićenja najbolje opisuje HCM-ovim i Singapur modelom. Na osnovu rezultata testiranja usvojen je Akcelikov model za proračun eksploatacione brzine na osnovu kojeg bi se mogao utvrđivati Nivo Usluge na gradskim saobraćajnicama sa standaradnim rastojanjem između raskrsnica na kojima postoji koordinisani rad signala u lokalnim uslovima.

KLJUČNE REČI

gradske saobraćajnice; Nivo Usluge; brzina-protok kriva; vreme putovanja;

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